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Comparison of the embodied energy of a grinding wheel and an end mill

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Abstract

In this paper, measurement results of the embodied energy of a corundum grinding wheel and a coated cemented carbide end mill are presented. Both tools are industrial standard regarding geometry and composition. The single process steps and their energy demands for the manufacturing of both tools is analyzed and compared. In addition, based on literature values, their respective wear behavior machining Inconel 718 is compared. Despite a much higher embodied energy of the grinding wheel compared to the end mill, it is shown that the required embodied energy to machine a specific volume of material (J/mm³) is considerably lower for the grinding wheel.

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1. Introduction

Energy demand and energy efficiency in manufacturing is an issue of increasing importance. This is reflected by numerous projects and papers dealing with Life Cycle Assessment of manufacturing processes (for an overview refer to [1]). Evaluating and comparing the energy demand of the most common material removal processes drilling, milling, turning and grinding, the latter always appears worst. However, as pointed out in recent work [2], abrasive processes like grinding offer an enhanced sustainability when considering the Life Cycle of the machined products. Due to the achievable superior surface properties applying abrasive processes when machining products exposed to friction (e.g. bearings, guides), less friction, less energy losses and higher lifetimes are achieved, resulting in an overall improved energy balance of the process chain.

Sustainability considerations of grinding including the whole process chain and the Life Cycle of the machined product is a rather new research field [3]. In [4] it was pointed out that all aspects have to be considered in order to conclude the sustainability comparison of grinding. Tooling for example is up to now a rarely considered aspect within the life cycle view [5]. The manufacturing of grinding tools can highly contribute to the energy consumption of the whole manufacturing chain [6] and at the same time can highly influence surface quality event for the same energy consumptions [7].

This paper will add a new aspect to this topic: the evaluation of the embodied energy of grinding tools (grinding wheels) in comparison to milling tools (end mills). As there is no general method to assess the embodied energy of tools, the method applied in this study will be described in detail. After presenting the embodied energies of both the grinding and the milling tools, their performance with respect to tool life and achievable material removal of Inconel 718 in relation to their respective embodied energy will be evaluated based on literature values. In addition, these values will be correlated to process energies and times.

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2. Method

2.1. Embodied Energy

The total amount of energy that is required for manufacturing a product, including the energy demands of its primary products, the energy for transportation and disposal, is known as embodied energy. It does not include the energy the product requires during its lifetime, e.g. the electrical energy of driving units. One of the main challenges calculating the embodied energy is the determination of the level of detail and the balancing boundaries of the assessment. One guideline that assists to make technological energy data available is the cumulative energy demand (CED). It helps to prepare the data in a uniform framework without strict prescriptions and allows the evaluation and comparison of products with respect to energy criteria. The cumulative energy demand aggregates the entire amount of energy for production (CED_p), use (CED_u) and disposal (CED_d) of products [8].

In this paper, the amount of energy that is necessary for manufacturing a corundum grinding wheel and a cemented carbide end mill is assessed and furthermore connects their embodied energy with their wear behavior. Therefore the system of CED_p is employed to identify the amount of energy that is required for manufacturing the products. CED_u is zero for tools, as they do not consume energy themselves during machining. The assessment of CED_d of the tools is not part of this study. CED_p according to [8] includes the sum of energy for the production of the product itself as well as the energy e.g. for the production, transportation, disposal, etc. of the primary material (CED_p + CED_u + CED_d of primary material and products). A common tool for balancing CED_p are process chain analyses. Therefore a macro analyses of each production process was done, the sensitive process steps (those with a high energy consumption) were identified and examined. The data was recorded with an industrial network analyzer during several cycles at each machine tool; the value for the energy was calculated at least from three independent measurements. In doing so it was ensured that the influence of differing process times (as common in production of the tools) was minimized. In contrast to CED_p the energy for transportation was not included here: during the measurements only the electric energy was recorded. There is only one exception, the consumption of gas during firing process was also included. The study also included the embodied energy of the primary products based on literature values.

2.2. Corundum grinding wheel

The investigated grinding wheel was an industrial standard for creep feed grinding materials such as Inconel. Its specification is given in Table 1. The grinding wheels geometry regarding DIN ISO 525 was shape 1 and the maximum work velocity was 50 m/s. The grain material used for the grinding wheel was a composition of white and pink fused alumina (corundum). The grain size was differed in a specific range to extend tool life and improve geometric accuracy. The grinding wheel was manufactured by Lapport Schleiftechnik GmbH, Enkenbach-Alsenborn, Germany; the measurements were conducted in the shop floor.

Table 1. Specifications of the corundum grinding wheel.

Bond	vitrified
Grain type	pink and white fused alumina
Grain size	F 100 / X
Dimension D x T x H	500 x 32 x 203.2 mm

2.3. Coated cemented end mill

End mills with geometries according to DIN 6528 were investigated. Their specifications are given in Table 2. The cemented carbide end mills were manufactured at the Institute for Manufacturing Technology and Production Systems (FBK), including both the manufacturing of the end mill itself and the coating. Geometry and coating of the end mills correspond to industrial standard for applications such as milling of Inconel.

Table 2. Specification of the coated end mill.

Cemented carbide	K30-K40
Diameter	10 mm
Length of blank	73 mm
Weight of blank	87 g
Weight of end mill	77 g
Number of teeth	4
PVD-coat	AlTiN

3. Embodied energy of a corundum grinding wheel

The embodied energy of the grinding wheel was determined at the grinding wheel manufacturer's factory. Due to confidential agreements, amounts and names of materials cannot be specified in detail.

To gain information about the energy that was used for manufacturing of the grinding wheel the process chain was analyzed and energy hot spots were determined, see Fig. 1.

Beside the production of the grinding wheel with its sensitive steps mixing, pressing, drying, firing, and final machining, the primary products for the grinding wheel also include high embodied energies. Those materials were not produced by the grinding wheel manufacturer himself. Therefore, beside the measurement of the sensitive process steps, the embodied energy of the primary products for the material mixture of the grinding wheel was determined using information from literature and databases. These values do not include the energy for transportation to the factory of the grinding wheel manufacturer. Because of the low mass of material that one grinding wheel contains in contrast to the large mass of material that is typically transported via trains and trucks over relatively short distances in one load, the raise of embodied energy by transportation per 1 kg is neglected.

3.1. Energy of primary products for the material-mixture

The primary products for the grinding wheel can be separated into three main groups:

- Grain material
- Bond material
- Auxiliary material

With an average value of 9 MJ/kg for corundum [9] the grinding wheel contains 110.38 MJ embodied energy from the grain material.

The vitrified bond of the grinding wheel mainly encloses two types of glass drips and feldspar. Due to the close relation of glass drips to glass an average amount of energy for the glass drips of 11.88 MJ/kg [10] is used. The feldspar contains around 1.30 MJ/kg [11]. All together the bond material of one grinding wheel contains 18.42 MJ embodied energy.

The embodied energy of the auxiliary material (water, binder) is neglected because of its low proportion in contrast to the other primary materials (the proportion e.g. of water is 64.8 J/kg) [12]. Summing up the total embodied energy of the primary products for the material mixture of one grinding wheel 128.80 MJ result.

3.2. Energy of sensitive production steps

In Fig.1 the sensitive steps of the process chain are highlighted. Those steps were identified as critical because they were done primary with machine tools and they hence highly contribute to the embodied energy of the production process. In contrast, the other process steps are mostly done by hand, so referring to CED, their contribution is excluded. Furthermore, if electric tools are used there, their contribution to the electric energy is negligible. So the following process steps will be discussed:

- Mixing and sieving of the grain and bond materials
- Pressing of the mixture to a green body
- Drying of the green body for vaporizing glue and auxiliary material
- Firing in a furnace
- Final mechanical machining, divided into machining of plane faces, borehole and peripheral face

The fundamental mixing of the primary products for the grinding wheel's mixture is done in several steps:

- Premixing of the different grain types
- Wetting the grains
- Adding bond materials
- Adding glue and auxiliary material

After mixing the components the base material is sieved to loosen up the mixture and to avoid conglomerate formation. The sieving is done, like mixing, with an electrical machine. Overall the mixing and sieving of the grain-bond-mixture contributes to the embodied energy with 0.06 MJ per grinding wheel.

The mixture is then transported to a hydraulic press where it is filled into a mold by hand and smoothed by a mechanical unit. The pressing process of the green body is volume controlled, i.e. the hydraulic cylinder is moved to a given position (in contrast to pressure controlled pressing, where the final pressure of the hydraulic press is used for process control). The part of embodied energy from pressing is 1.56 MJ.

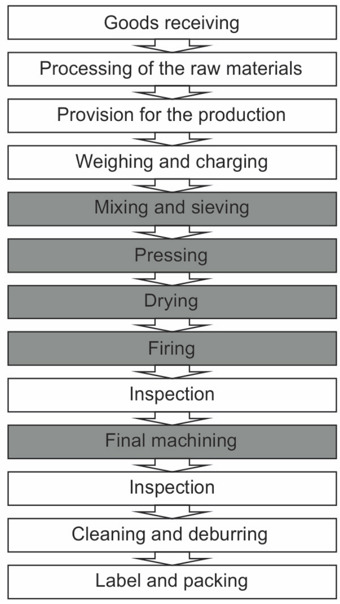

Fig. 1. Analyzed process chain for manufacturing a grinding wheel with highlighted energy sensitive steps

Before the green body can be fired it needs to be dried in an oven to get rid of glue and auxiliary material that helped mixing and pressing the green body. The drying process takes place in a drying oven at 250° C for 24 h. The oven is always charged with different types of grinding wheels, regarding size and type. To gain information about the energy of one specific green body, the oven's useable volume and the green body's volume was calculated. With the drying oven's measured energy consumption it is possible to gain the data for the specific green body, 0.54 MJ.

The firing of the green body was done in an alternate working top hat furnace fired with gas. Thus, beside the measurement of the electrical energy consumption the consumption of the gas was also measured. The firing took place over a period of around 7 days. The calculation of the specific embodied energy per grinding wheel (after firing the green body it is named grinding wheel) is analog to the calculation for the drying process (determination of oven volume and grinding wheel volume). The amount of embodied energy from firing for one grinding wheel is 100.22 MJ.

The last process in the production of the grinding wheel that was identified as a sensitive step in the process chain is the final mechanical machining of the grinding wheel to adjust its geometrical shape (machining of the plane faces, the borehole and the peripheral face). The whole machining resulted in an embodied energy of 0.85 MJ per grinding wheel.

Summing up the embodied energy that the grinding wheel consumed during the manufacturing process (overall 103.23 MJ) including the energy of the primary products that were included in the grain-bond-mixture (128.80 MJ) it can be stated that one grinding wheel contains a specific embodied energy from production of 232.03 MJ (see also Table 3).

Table 3. Embodied energy of a corundum grinding wheel.

Primary products	**128.80 MJ**
Grain material	110.38 MJ
Bond material	18.42 MJ
Auxiliary material	neglected
Manufacturing	**103.23 MJ**
Mixing & sieving	0.06 MJ
Pressing	1.56 MJ
Drying	0.54 MJ
Firing	100.22 MJ
Final machining	0.85 MJ
Total embodied energy	**232.03 MJ**

4. Embodied energy of a coated cemented carbide end mill

Similar to the approach for determining the embodied energy of the primary products of the corundum grinding wheel a literature research was done to gain the information of the energy that is needed to produce the cemented carbide blank.

The production of the end mill itself (after production of the blank) includes the processes (see Fig. 2):

- Grinding of the end mill's geometry in a tool grinding machine
- Preparation of the end mills cutting edge
- Cleaning of the end mill
- Coating with a PVD thin film coat (physical vapor depositing)

Those processes were performed at the FBK. The energy input for those processes was acquired using the industrial network analyzer mentioned in section 2.

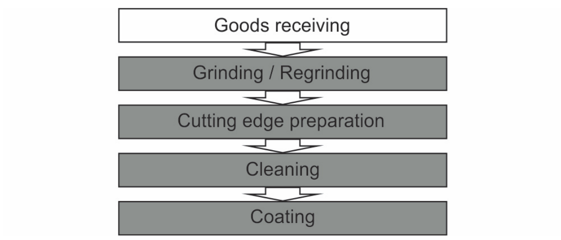

Fig. 2. Process chain for manufacturing an end mill

4.1. Embodied energy of the cemented carbide blank

In [13] different types of production processes for carbide blanks were analyzed in the shop floor of a manufacturer. The different forming processes employed, each including sintering and post processing were:

- Die pressing (18.5 MJ/kg)
- Cold isostatic pressing (25.55 MJ/kg)
- Screw extrusion (35.72 MJ/kg)
- Ram extrusion (37.22 MJ/kg)

Beside the differences in the processes themselves, the authors conclude that the high deviations in the embodied energies of the blanks results from the lengths of the rods. Those cannot completely be freely selected and are linked to the processes. A result of the different lengths of the rods is a differing packing of the furnaces, highly influencing the energy demand for sintering. For details on the production of the blanks applying the different production methods please refer to [13].

The die pressing process delivered blanks with a diameter of 10 mm and a length of 73 mm. Because this dimensions were the same as used in this study the energy of the die pressing process will be used for further examinations. This is due to the author's note that a proportionality cannot be guaranteed [13] and because it is the most efficient process (it has to mentioned that only screw extrusion is capable of bringing coolant channels into the blank for internal cooling, favorable for drilling processes).

As the study of [13] did not include the embodied energy of the primary products for the rods, this energy needs to be added. From [10] an average embodied energy for the tungsten carbide powder with 10 % cobalt of 90 MJ/kg is anticipated. With an energy of 1.54 MJ for die pressing considering the weight of the blank (0.083 kg), the embodied energy of one tungsten carbide blank with the specified geometry is 9.01 MJ.

4.2. Embodied Energy from grinding and coating

The grinding of the end mills geometry was done with an industrial standard tool grinding machine. The blank loses 10 g weight during the grinding process (final weight of end mill is 0.073 kg). To ascertain the energy input of the grinding process, the electrical energy consumed by the machine from clamping to declamping the end mill was measured (including auxiliaries like fans and idle times). The amount of embodied energy from grinding the end mill is 6.08 MJ. In industrial application it is common to regrind cemented carbide end mills. For this study, it is expected that an end mill can be reground four times. Regrinding needs much less energy because the tools geometry is only restored (e.g. flank and rake face). It was examined that regrinding only needs 35 % of the energy for grinding a new end mill, so the embodied energy for regrinding is 2.13 MJ.

The cutting edges of cemented carbide end mills are prepared to increase coat adhesion. At FBK, cutting edge preparation processes applying grinding and laser are investigated; however, there is no drag-finishing unit available, an industrial standard for cutting edge preparation. This missing data was provided by a tool manufacturer. It can easily be calculated by the energy consumption of a drag-finishing unit (2.5 kW), the packaging capacity (24 pieces) and the process time (300 s). A share of 0.03 MJ for the cutting edge preparation per end mill to the embodied energy resulted.

After cutting edge preparation and before coating in a PVD coating system the end mills need to be cleaned. At FBK the tools are cleaned with the same methods (heated ultrasonic baths) but in a much smaller scale, resulting in a relatively high energy demand per end mill. In industrial application, those facilities have a high productivity, why it is assumed here that this process step can be neglected. Future examinations could take this process into consideration.

The coating of the end mills was done in a small industrial PVD standard facility. The energy demand for coating with two arc evaporators is 52.75 kWh and additional 35.35 kWh for the cooling system. The capacity of the PVD coating system was 120 pieces (with a diameter of 10 mm). All together the coating of the end mill adds 2.64 MJ to the embodied energy.

In sum the embodied energy of an end mill that is used only once is 17.76 MJ (Table 4). If it is reground four times his embodied energy raises to 36.96 MJ (one blank, one original grinding process, four regrinding processes, five cutting edge preparations, five cleaning and coating processes).

Table 4. Embodied energy of an end mill.

Primary product	**9.01 MJ**
Carbide blank	9.01 MJ
Manufacturing	**8.75 MJ**
Grinding	6.08 MJ
Cutting edge preparation	0.03 MJ
Cleaning	neglected
Coating	2.64 MJ
Total embodied energy	**17.76 MJ**

5. Comparison of the wear behavior of a grinding wheel and an end mill

The embodied energy of a corundum grinding wheel is 232.03 MJ, that of an end mill only 17.76 MJ. However, the embodied energy has to be related to the amount of material that can be removed by the respective tools to further assess their sustainability. For this evaluation, machining of Inconel 718 was used, surface grinding of slots and side milling of slots.

The wear of grinding wheels is commonly expressed by the G-ratio, the ratio of removed material to volume of wheel wear. In [14], applying a grinding wheel speed of 30 m/s, feed rate of 600 mm/min, width of cut of 25 mm and a depth of cut of 1 mm, a G-ratio when machining Inconel 718 of five resulted (this can be regarded as a low value). The corundum grinding wheel evaluated in this paper can be used down to a diameter of 300 mm. This results into 4,021 cm³ usable tool volume and hence in a possible removable material volume of 20,105 cm³.

In [15], applying a cutting speed of 25 m/min, a feed of 0.025 mm and a depth of cut of 2.5 mm with an end mill similar to the one evaluated in this study (diameter of 10 mm and four teeth, AlTiN coating), 22 cm³ of removable material volume (Inconel 718) result until end of tool life. Assuming four possible regrinding cycles after end of tool life, as mentioned in section 4, 110 cm³ Inconel can be machined with one end mill. That means to remove the same amount of Inconel as the corundum grinding wheel, 914 end mills without and 183 end mills with four times regrinding are needed.

With the embodied energies of the tools, as determined in section 3 and 4, a ratio of required embodied energy to machinable material volume of 11.54 kJ/cm³ results for the corundum grinding wheel and 336 kJ/cm³ for an end mill that was reground four times (807.27 kJ/cm³ without regrinding). That means although the grinding wheel requires a considerably higher embodied energy than an end mill, a much better energy balance is achieved by the grinding wheel. In addition, shorter process times are reached in grinding. For the examples used here, a process time to remove 20,105 cm³ Inconel 718 of 22.34 h for grinding and 168.38 h for milling result. Shorter process times also highly contribute to enhanced sustainability. Moreover, the process times when milling the same workpiece quality as with grinding will likely be even higher than in these calculations. The results on embodied energy and process time are summarized in Fig. 3.

In this Figure, the embodied energy is calculated by the embodied energy of one tool multiplied by the required number of tools to machine 20,105 cm³ Inconel 718. For grinding, 232.03 MJ result, for milling 16,230.22 MJ and 6,755.28 MJ with four times regrinding of the end mill respectively.

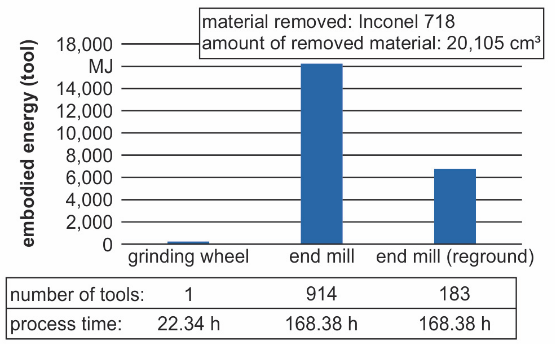

Fig. 3. Required embodied energy, number of tools and process time (without set-up and non-productive times) to remove 20,105 cm³ of Inconel 718

The evaluation of the process times had to take the times for dressing the wheel and the set-up times for both grinding and milling into account. However, as only 22 cm³ of Inconel can be machined with one end mill until end of tool life, and nearly a thousand times more with one grinding wheel, those times would be considerably higher for the milling process.

However, there are a lot of simplifications and boundary conditions that have to be considered for a final assessment of this aspect of process sustainability. The first thing is the machined workpiece. To really compare the energy balance of the tools, the same workpiece quality, concerning accuracy of shape and size as well as workpiece roughness, had to be machined. Therefore, the process parameters had to be adjusted, probably resulting in different wear behaviors of the tools. The second thing to be included is the energy needed for machining the workpieces, taking all auxiliaries into account (e.g. fans, cooling facilities, chip conveyers, etc.). Grinding requires more energy to remove a specific workpiece volume than milling, as stated in the introduction. For grinding, specific energies (ratio of required process energy without auxiliaries, commonly the spindle power, to remove a volume of material) are ranging from 10 to 200 J/mm³ (strongly depending on the chosen parameters and achieved workpiece quality, see [2]), in this case about 32 J/mm³ [14]. Milling typically ranges from 2 to 10 J/mm³. Adding the ratio of embodied energy of the tools to machine a volume of material, what could be named the specific embodied energy, to the specific energies, about

44 J/mm³ for grinding and 340 J/mm³ for milling result. This in fact shows that, contradictory to what is generally assumed, a better energy balance can be achieved via grinding.

6. Conclusion and Outlook

In this paper, an assessment of the embodied energy of a common corundum grinding wheel and a coated cemented carbide end mill was performed. The grinding wheel has a total embodied energy of 232.03 MJ and the end mill 17.76 MJ. Assuming that the end mill can be reground four times, an embodied energy of 36.96 MJ results (with a fivefold tool life).

Despite a much higher embodied energy of the grinding wheel a higher sustainability is achieved, as the grinding wheel is capable of machining a considerably higher volume of material. The ratio of required embodied energy to a volume of removed material (Inconel 718), what could be named the specific embodied energy, is 11.50 J/mm³ for the corundum grinding wheel and 336 J/mm³ for the end mill that was reground four times (807.27 J/mm³ without regrinding).

This value has to be extended with the energy needed for the machining process itself (specific energy). As grinding requires higher specific energies than milling, the difference in the energy balance will get smaller. Adding common specific energy values to the specific embodied energies, about 44 J/mm³ for grinding and 340 J/mm³ for milling result. This shows that grinding can result in a better energy balance, contradictory to what is generally assumed. It has to be mentioned that all auxiliaries (fans, cooling system, etc.) have to be taken into account for a final assessment and the same machining task (workpiece quality and shape) has to be examined. Finally, dressing of the wheel and the associated loss of abrasive volume also has to be considered.

To remove the same amount of material (Inconel) as the grinding wheel, 914 end mills (or 183 end mills that are reground four times) are needed. That means to remove the same amount of material as one grinding wheel via milling, 914 clamping and declamping cycles are needed (also when regrinding the end mills), resulting in much higher set-up and non-productive times (in addition to much lower process times for grinding, as evaluated in this study). Another aspect to be examined is the disposal of the tools CED_d (one grinding wheel to 183 end mills), not investigated in this study.

This investigation shows that for an assessment of the sustainability of a process, especially for grinding, the whole process chain has to be considered. Considering the process only, grinding appears to be worse than cutting processes because of higher specific energies. Taking the tools into account, the energy balance is better for grinding due to considerably lower specific embodied energies.

Finally, as stated in [4], the properties and the complete Life Cycle of the products has to be considered as well, as products machined applying abrasive processes can reach an enhanced sustainability via adapted process parameters through reduced friction and energy losses.

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